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TEST RESULTS FROM A TWO-STAGE TRAVELING CHARGE LIQUID PROPELLANT GUN

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13. ABSTRACT (Maximum 200 words)

Test data for a 40-mm fractional traveling charge (FTC) gun system are described. The system consists of a hybrid propulsion method using a solid propellant booster charge and a liquid propellant traveling charge. The purpose of the two stage propellant system was to create a traveling charge gun with a delay mechanism created by a separator piston between the solid and liquid charges.

The data showed increased performance when compared to the Mayer Hart model, for projectiles less than 250 grams and charge to mass (C/M) ratios of less than 2. Tests fired at C/M greater than 2 with heavy projectiles yielded high pressures in the long liquid charges.

The combustion of the second stage of the traveling charge produced waves that were tracked in a space time manner for one of the FIC rounds. The calculated wave speed gave reasonable agreement when compared with estimated sound speeds determined from chamber measurements in other regenerative fixtures.

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1. INTRODUCTION

General Electric Tactical Systems Department investigated a possible traveling charge concept using a regenerative liquid propellant gun (RLPG) (Mandzy 1989). The concept is referred to as a Fractional Traveling Charge (FTC).

Earlier, Ashley (1976) had tested a similar device, called a cavity generator, in an attempt to control the ignition and combustion of a bulk loaded liquid propellant gun. His results were not definitive. Later, Knapton et al. (1983) tested a similar device in a 37-mm hybrid gun. Their study produced some promising results, as shown by Morrison et al. (1988), but again the results were not conclusive.

In the more recent General Electric study, Mandzy (1989) reported that velocities near 2000 m/s were achieved with the FTC concept in a 30-mm gun using projectile masses of 110.5 g. For comparison, this projectile mass scales to 262 g for a 40-mm gun. By increasing the charge to mass ratio (C/M) to 6.3, achieved by reducing the projectile mass to about 35 g, Mandzy was able to increase the projectile velocity to around 2900 m/s. Again, as a comparison, the 35 g projectile scales to 83 g for a 40-mm gun.

We tested the FTC concept in a 40-mm hybrid liquid propellant gun in an attempt to accelerate a 225 g projectile to velocities higher than what might be expected from either conventional liquid or solid propellant propulsion systems.

The hybrid liquid propellant gun contains a two-stage combustion system. The first stage consists of a center core ignited solid propellant charge. The first and second stages are separated by one or more piston separator devices, which were developed by General Electric. The second combustion stage consists of a bulk loaded liquid propellant that serves as the traveling charge component.

In our study, we varied the C/M by changing the amount of liquid propellant in the second stage of the combustion process. This approach was selected to keep the projectile mass constant at 225 g for the 40-mm gun. We also performed a few preliminary tests where the projectile mass was varied from 144 g to 277 g.

2. APPROACH

A smooth bore 40-mm gun manufactured by the University of Dayton was used to perform the hybrid liquid propellant tests (Bauer 1979). This gun has a travel of about two meters. The gun has 13 pressure transducer ports for both quartz gages or minihat strain transducers (Brosseau 1970).

Several projectile designs were considered for the 225 g projectile. The first projectile was a simple right circular cylinder made from 7075 aluminum with an "O" ring seal which served as an obturator. This design provided minimum bore resistance and consequently little shot start pressure. An additional problem with the "O" ring obturator was blow-by that obscured the interferometer signal during the second stage combustion. The problem of projectile obturation was first addressed using a nylon tail seal obturator (Watson 1987) that reduced blow-by and significantly increased bore resistance. However, radiographic results of interior ballistic tests in fiberglass tubes confirmed the suspicion of a lack of structural integrity of the nylon tail seal. Attempts were then made using variations of a sleeve technique attached to the projectile to eliminate wall effects of the second combustion stage. The attempt was not successful.

The final projectile design was a modification of projectiles used in our earlier 37-mm and 38.8-mm bulk loaded liquid propellant gun programs (Knapton 1983). These projectiles used nylon obturation bands that provided more bore friction and increased the effective shot start pressure. In our earlier tests, the nylon bands and nylon disc at the base of the projectile provided adequate obturation to record the interferometer signal throughout the entire tube in the 37-mm and 38.8-mm tests. However, with the 40-mm FTC test, there was still loss of the interferometer signal during the second stage combustion.

The first stage of the combustion process consisted of a center core igniter containing an electric match with 1 g of FFFg black powder along with 5 g of single perforated black powder pellets that were placed inside a 6-mm diameter plastic straw. The black powder pellets were 6 mm long with a 5-mm outside diameter and a 1-mm inside diameter. The black powder pellets, black powder and the electric match were held in the straw with nitrocellulose glue.

This center core igniter was contained in a cellophane bag with 130 g of single, perforated M5 propellant. The entire first stage charge was about 30 mm in diameter and about 200 mm long.

The second stage of the combustion process was a hydroxylammonium nitrate based monopropellant, LP 1846 (Freedman and Travis 1981). The monopropellant was introduced into the gun tube between the projectile and the separator piston with a syringe to minimize ullage in the second stage. In some of the later tests the liquid propellant second stage was preloaded in a nylon sleeve to eliminate gun tube wall effects. In the nylon sleeve tests, care was also taken to completely fill the sleeves to eliminate ullage in the second stage.

The separator pistons were nylon devices that were designed, as was done by Ashley (1976), Knapton et al. (1983) and Morrison et al. (1988), to control the formation of the combustion cavity in the bulk loaded liquid propellant second stage. Figure 1 shows the separator pistons used in the present FTC firing tests.

3. EXPERIMENTAL RESULTS

The first series of tests was fired with various projectile masses to evaluate the effectiveness of the FTC concept. The method chosen for evaluation of a possible traveling charge was a comparison of the FTC performance with a Mayer-Hart calculation (Mayer and Hart 1945), which approximates the performance of a solid propellant gun.

The results of the first group of FTC firings in the 40-mm hybrid gun are summarized in Table 1. The tests were all performed with the General Electric separator piston (shown in Figure 1A). The maximum pressure listed in Table 1 is the maximum pressure measured at any pressure gage, not necessarily the breech pressure. The maximum pressure at any gage was selected for the pressure used in the Mayer-Hart calculation. The measured muzzle velocity is based on the average velocity measured between the first and second break screens located at 4 and 7 meters from the muzzle. The percent Mayer-Hart value indicated in Table 1 is the percentage change in the measured muzzle velocity compared with the Mayer-Hart solid propellant muzzle velocity. The Mayer-Hart percentages are not shown for

the rounds where there was suspected projectile failure. The Mayer-Hart calculations for these rounds would be based on an erroneous projectile mass for part of the travel.

Ident. No. 411-16 was fired without a separator piston, a 226 g solid propellant charge, or a liquid propellant charge. This round resulted in a negative Mayer-Hart percentage, which indicates a less than idealized solid propellant charge firing and no traveling charge effect. The significant nine percent gain over Mayer-Hart calculations shown in Ident. Nos. 411-13 and 411-14 indicate that a traveling charge may have caused the increase in performance. The results of Table 1 were considered encouraging enough to pursue further studies and with larger projectile masses.

Table 1. Initial FTC Tests in 40-mm Hybrid Gun.

Ident. No.	Projectile Mass (9)	LP1846 Mass (g)	C/M	Maximum Pressure (MPa)	Muzzle Velocity (m/s)	Mayer-Hart (%)
411-1	*163.6	129.6	1.62	475	1743	---
411-2	*150.0	103.4	1.60	325	1577	---
411-4	*154.0	132.5	1.74	460	1846	---
411-5	*159.0	127.4	1.66	240	1725	---
411-6	*153.3	119.4	1.67	225	1811	---
411-7	155.3	117.2	1.63	305	1689	0.80
411-8	*148.5	123.8	1.75	275	1728	---
411-9	149.3	120.9	1.72	340	1687	-4.5
411-10	144.5	118.7	1.76	375	1745	-1.9
411-11	277.0	123.8	.94	280	1401	0.70
411-13	196.6	203.8	1.73	290	1763	9.1
411-14	150.0	269.4	2.70	350	2011	9.0
411-16	157.2	---	1.48	490	1772	-4.2

* projectile failure

The second series of FTC tests was an attempt to optimize the performance of the fixture with projectile masses of about 225 g. Five of the first six rounds in this series (Ident. Nos. 411-31 through 434-3) were unsuccessful attempts to launch projectiles intact with the obturating tail seals described earlier. Ident. No. 434-13 had an obturator tail seal that incorporated the sleeve container for the second stage of the combustion. The results of the second series of FTC tests are summarized in Table 2.

Table 2. Performance Optimization Tests With the Hybrid 40-mm Gun.

Ident.	Projectile Mass (g)	LP1846 Mass (g)	C/M	Maximum Pressure (MPa)	Muzzle Velocity (m/s)	Mayer-Hart (%)
411-30	222	113.6	1.10	300	1521	2.1
411-31	*231	160.5	1.26	352	1580	---
411-32	*227	379.1	2.24	540	1789	---
411-33	*230	667.4	3.46	---	1780	---
434-1	*239	316.0	1.87	---	1828	---
434-2	*237	130.6	1.10	350	1588	---
434-3	*223	319.5	2.02	575	2099	---
434-4	220	558.1	3.12	575	2041	2.8
434-5	223	580.8	3.19	500	2186	12.0
434-6	223	1036.6	5.23	675	2335	17.1
434-7	224	994.0	5.02	>750	2153	8.3
434-8	236	569.4	2.96	>750	2092	11.0
434-9	237	604.9	3.10	>750	2046	7.7
434-10	236	616.3	3.16	>750	2125	11.5
434-11	235	346.5	2.08	400	1862	11.0
434-12	235	363.5	2.10	>825	----	---
434-13	269	269.8	1.49	500	----	---
434-14	236	318.1	1.90	360	1894	15.6
434-15	236	719.9	3.60	>618	2107	10.5

* projectile failure

The results from the FTC tests were not considered acceptable. The first seven tests (Ident. Nos. 411-30 through 434-03) resulted in only one test (Ident. No. 411-30) where the projectile was launched intact. This test was fired at a low C/M of 1.1 and was not considered

further for high velocity applications. There was some indication from the first seven tests that the maximum pressure seemed to increase as a function of the amount of liquid propellant.

It was postulated that the length of the liquid bulk charge may be a factor in generating increased pressures. It was indicated by Knapton et al. (1985) that the increased length of bulk loaded liquid propellant charges tended to increase the maximum pressure along with a lack of combustion control. The next five tests (Ident. Nos. 434-4 through 434-8) were attempts to reduce the maximum pressure by using more than one separator piston. Ident. No. 434-4 used two of the General Electric separator pistons (shown in Figure 1A), while the other four tests used a Figure 1A separator piston between the first and second stages and a Figure 1B separator piston between the second and third propellant stages. Ident. No. 434-6 had an additional liquid propellant stage with a second Figure 1B separator. These tests, with the exception of Ident. No. 434-4, resulted in pressures in excess of 650 MPa. The initial conditions of Ident. No. 434-4 were repeated for Ident. Nos. 434-9 and 434-10, which yielded unacceptably high maximum pressures. It was apparent from the pressure-time records for all the tests that the additional separator pistons did not effect the delay of combustion in the other liquid propellant stages. It was also apparent from this group that increasing the C/M, equivalent to increasing the amount of bulk loaded liquid propellant, resulted in increased chamber pressure.

Bulman, Koch and Maher (1987) reported some success in reducing the maximum pressure and increasing performance by eliminating wall effects between the liquid propellant and the gun chamber wall. Indent. Nos. 434-11 through 411-13 and 411-15 were attempts to reduce the liquid propellant-tube wall effects by using thin, nylon sleeves that were pre-loaded with liquid propellant. In all cases, the end of the liquid propellant sleeve was sealed with a 0.13-mm mylar window to allow ignition of the liquid propellant in the sleeve. The nylon sleeve was an integral part of the projectile for Ident. No. 434-13. The objective of this design was to make the sleeve serve as an obturator, as well as a container for the liquid propellant. Ident. No. 434-15 resulted in excessively high pressures. Indent. No. 434-11 apparently gave desirable pressure characteristics at a C/M of 2.08. However, Ident. No. 434-12, (an attempt to duplicate Ident. 434-11), had a maximum pressure greater than 825 MPa. Ident. No. 434-13 did not exhibit the amount of time delay that was desirable before the ignition of

the liquid propellant charge and there was a possible separation of the projectile and the nylon sleeve early in the combustion cycle. The lower maximum pressure of Ident. No. 434-13 can be attributed to the low C/M of 1.49.

Bulman, Koch and Maher (1987) claimed that the diameter, position, and number of holes determined the ignition delay due to the separator piston. In our study, the lack of ignition delay control between the liquid propellant stages raised the question of the effectiveness of the separator piston in delaying the combustion process. This question led to the firing of Ident. No. 434-14 as a test of the delay mechanism. This round was fired with no holes in the separator piston and an "O" ring seal between the separator piston and the chamber wall. There was a 0.7-m/s delay in the chamber pressure gage from the time of maximum pressure caused by the solid propellant charge to the first indication of ignition of the liquid propellant. This time can be compared to a 1.2-m/s delay in the chamber pressure gage from Ident. No. 434-3, fired with the standard separator piston and approximately the same initial conditions. In the case of Ident. No. 434-14, the lack of a direct ignition path, such as holes in the piston or a path around the piston (prevented by the "O" ring seal), actually seemed to decrease the delay time between the combustion stages.

4. DATA REDUCTION

4.1. Wave Diagram. The pressure time data from tests with the second stage combustion suggested the existence of longitudinal waves in the chamber and gun tube which propagated back and forth throughout the system. These wave motions were plotted on a space-time characteristic plot to determine the trajectory of each wave. The test examined here is Ident. No. 411-13. The pressure data for this test consisted of five pressure transducers with axial positions shown in Table 3. The pressure histories are shown in Figures 2 through 6, respectively. A 35-GHz doppler radar was used to measure the projectile position, which is processed to determine projectile velocity within the gun tube. Figure 7 shows the projectile velocity history.

Table 3. Gage Positions in Ident 411-13.

Gage Position	Distance from Rear Face of Tube (RFT) (mm)
Gage 2	34
Gage 5	567
Gage 6	619
Gage 8	887
Gage 9	1354

A review of the pressure histories in Figures 2 through 6 reveals significant wave structure. Information can be extracted from the pressure spikes by plotting the times at which the pressure spikes occur as a function of barrel position.

Examination of the response from pressure gage 2 (Figure 2) indicates a smooth hump as a result of the first stage solid propellant combustion. A pressure rise is observed during the first pressure decay. This pressure rise, due to the second stage burning, occurs at 29.8 msec and is identified as point 1 on Figure 2. This pressure rise continues due to the second stage combustion until point 2. Expansion during the ballistic cycle causes the pressure to decrease until a pressure increase is observed at point 3. The pressure pulse increases and reaches a maximum at point 4. Points 5 and 6 are possible reflections during the expansion. Points 1 through 6 correspond to six events that occur at pressure gage 2 (34 mm from the breech face) and are shown in Figure 8. Figure 8 is a plot of time versus position in the gun barrel measured from the breech face. This type of characteristic plot was used by Bulman, Koch and Maher (1987) to study transient effects of the events for the assumed traveling charge.

Examination of Figure 3, obtained from pressure gage No. 5, reveals several additional points in the space-time plane. The near vertical rise at point 7 corresponds to the time at

which the projectile passed the transducer port. The approximate linearly increase in pressure ends at point 8. The minor structure on the pressure rise between points 8 and 9 may be due to the separator piston passing the transducer port. The pressure peak following point 9 (which may be the same event recorded for the previous gage, but at a higher value) is assumed to be a result of the ignition of the second stage liquid propellant. This pressure is higher assuming the combustion of the second stage occurred beyond the pressure gage No. 5 position. Hence, the pressure from the event at point 9 in Figure 3 would be higher than the same event in Figure 2 at point 1. Points 10, 11 and 12 are also plotted at their appropriate space-time coordinates in Figure 8.

Similar events from the other pressure transducers in Figures 4-6 are plotted in Figure 8. The appropriate points were connected to reveal the trajectory of each wave. As time increases, the reflections become weaker and more difficult to identify. Knowing the space and time when the next event should occur aids in detecting the weak reflections. Figure 8 also contains the space-time position of the projectile as determined from the radar data.

The projectile is relatively easy to track in the characteristic plot using the radar data and the pressure transducers. The separator piston, on the other hand, has combustion on both sides and significantly less mass (35 grams for the General Electric version). The postulated separator plug motion is shown by the dashed line in Figure 8.

4.2. Sound Speed. The waves in the chamber travel through a complex medium consisting of solid and liquid propellant, the nylon piston separator, and the partially or completely burned propellants. The characteristic plot in Figure 8 offers the opportunity to examine the sound speed through the complex two-phase medium.

Two slopes in Figure 8 that are of some interest are the slopes based on the time at which the onset of the two dominant pressure pulses occur (i.e., the two pressure pulses which occur during the pressure decay). Taking the tangent of the two slopes in the region of pressure gages 5 and 6, gives values for a sound speed of 960 m/s and 1176 m/s, respectively. These numbers are probably no more accurate than ± 10 percent due to

inaccuracies in estimating the time of the pressure rise for each pulse, as well as the errors in estimating the slope. Interestingly, however, the lower sound speed occurs first, which one would expect due to the likely existence of a two-phase mixture early in the combustion process.

For comparison, the estimate of the sound speeds given here may be compared with estimates made by Watson and Knapton (1990), based on pressure oscillations in a 30-mm regenerative liquid propellant gun firing. They estimated sound speeds of 1009 m/s and 976 m/s, depending on the assumption of an annular chamber analysis on a circular chamber analysis. Also, for the same test conditions, Coffee (1987) (using his RLPG interior ballistic code and assuming delayed burning and a homogeneous two phase mixture) estimated an average sound speed of 976 m/s.

5. CONCLUSIONS

Tests with a hybrid 40-mm gun consisting of a solid propellant charge and a liquid propellant charge demonstrated an approximate 15 percent velocity increase over the Mayer-Hart prediction for a conventional solid propellant firing. The increase is attributed to a traveling charge. The performance was not optimized due to a lack of control in igniting the second stage (i.e., the traveling charge stage, which consisted of the liquid propellant). The cause for the lack of control was not identified; however, contributing factors may have been frictional heating and/or gas blow-by past a piston separator device.

The ignition of the liquid propellant second stage resulted in a large pressure pulse which was recorded on several pressure gages in the chamber and gun tube. A wave diagram plot (Figure 8) provided a means for estimating the sound speed, which increased from about 960 m/s to 1176 m/s (with an uncertainty of about $\pm$10 percent).

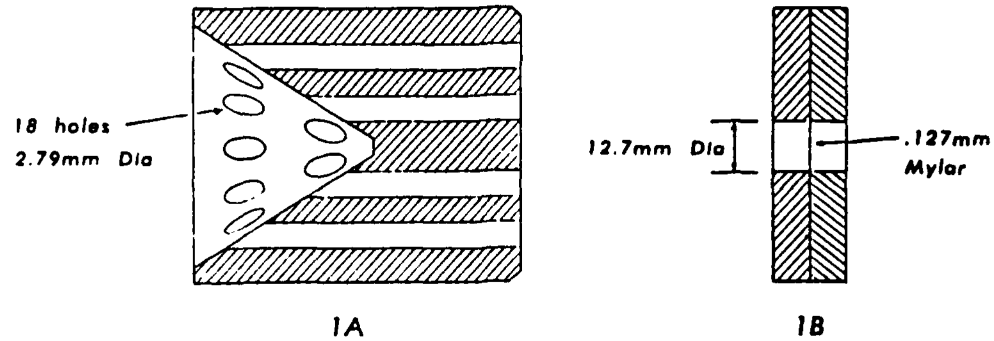

Figure 1. Separator Pistons Used in FTC Firing Tests.

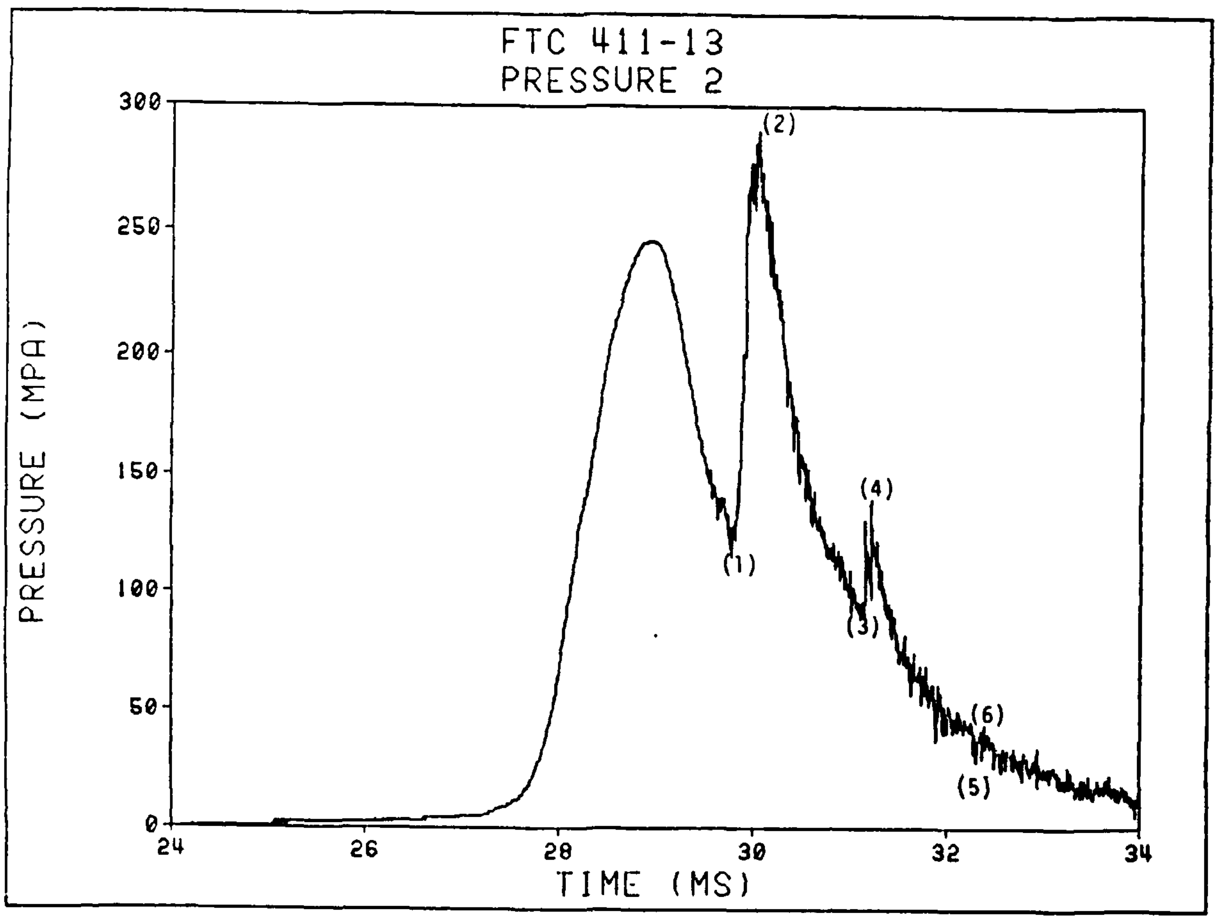

Figure 2. Pressure Gage Number 2 for Round 411-13.

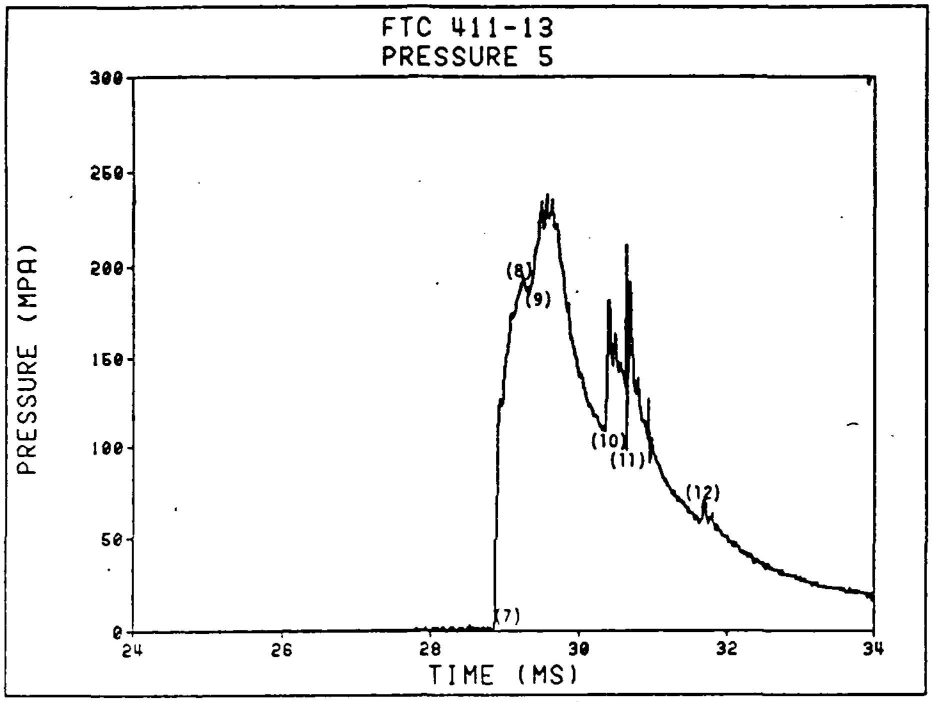

Figure 3. Pressure Gage Number 5 for Round 411-13.

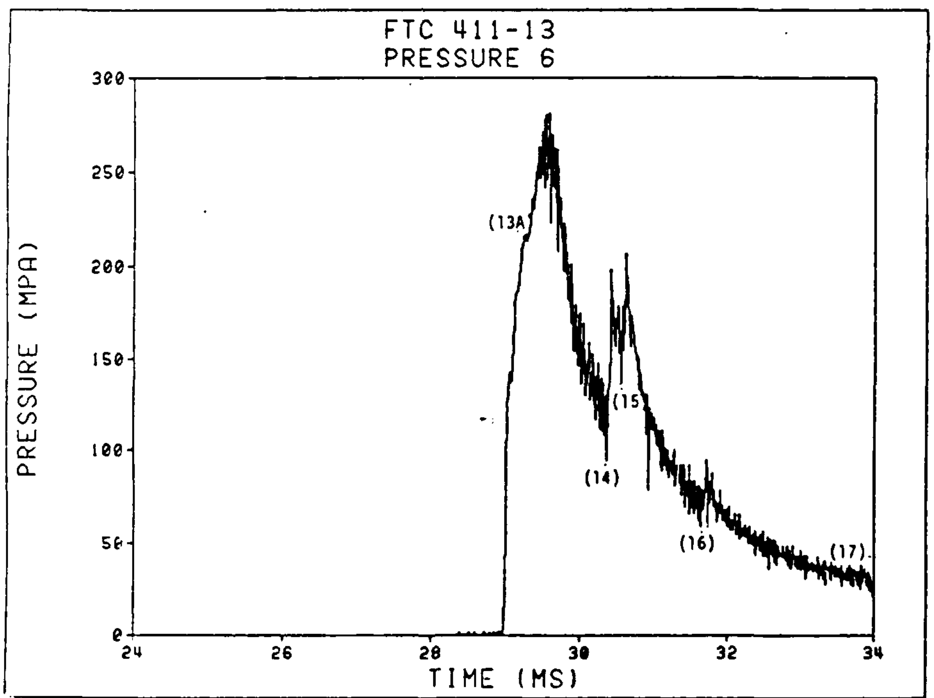

Figure 4. Pressure Gage Number 6 for Round 411-13.

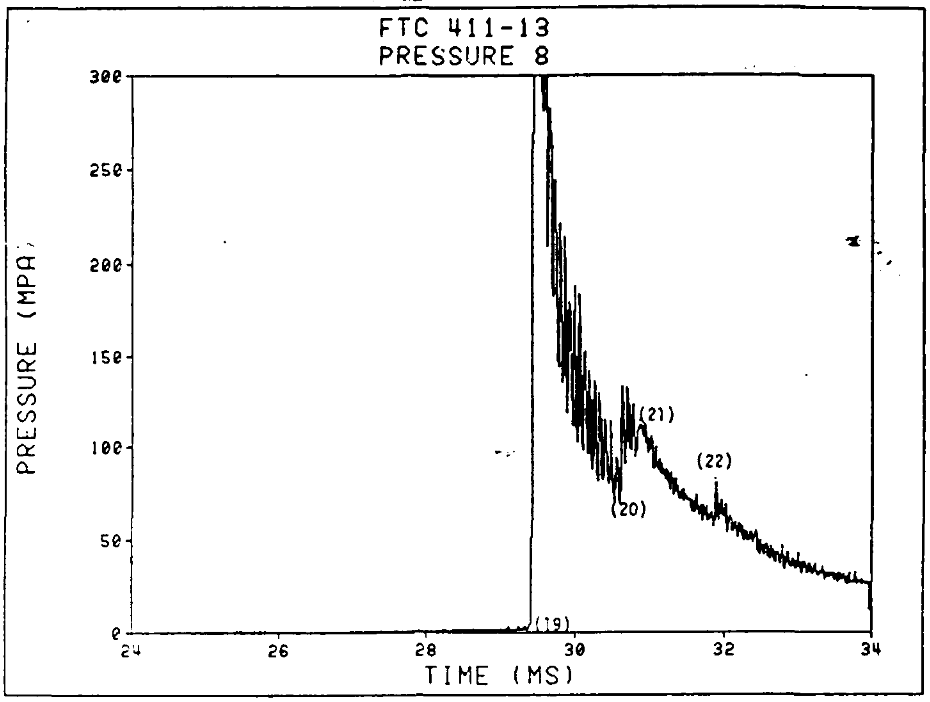

Figure 5. Pressure Gage Number 8 for Round 411-13.

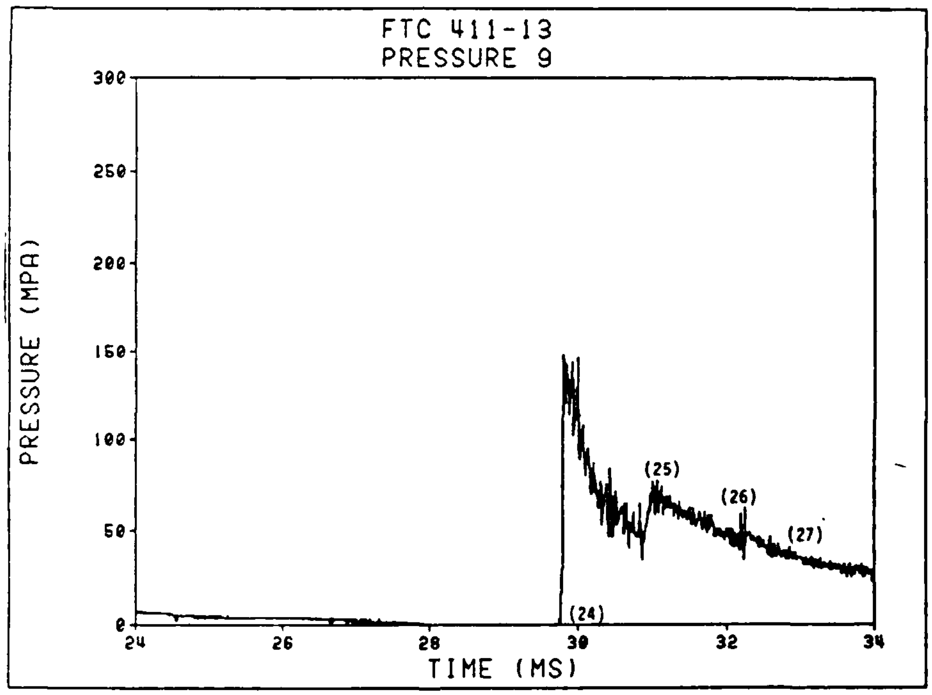

Figure 6. Pressure Gage Number 9 for Round 411-13.

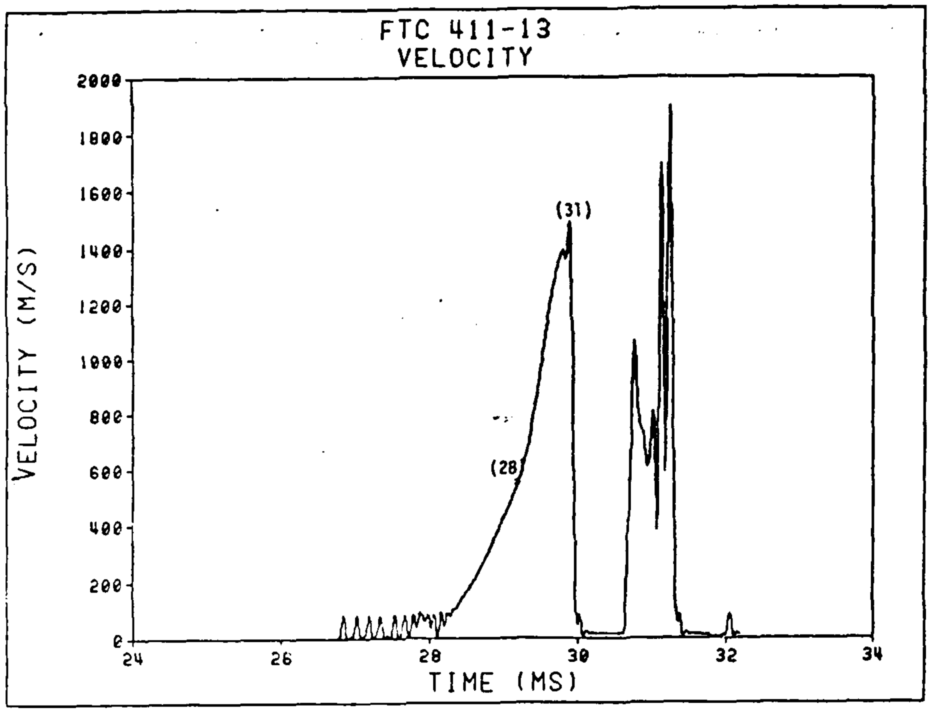

Figure 7. Projectile Velocity for Round 411-13.

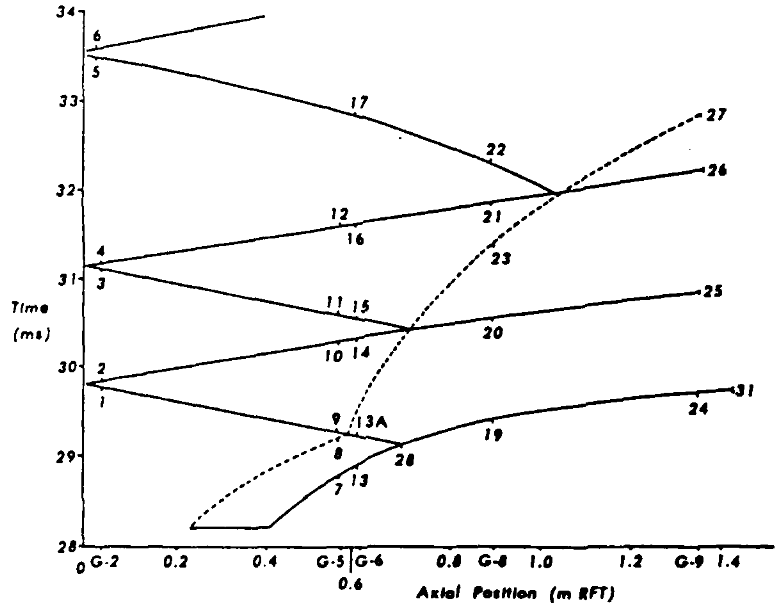

Figure 8. Characteristic Plot for Round 411-13.

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